Cosmic gamma-ray bursts

I. L. Rozental', V. V. Usov, and I. V. Éstulin†

Institute for Space Research, Academy of Sciences of the USSR, Moscow
Usp. Fiz. Nauk **140**, 97–115 (May 1983)

A summary is given of research on transient (duration $\approx 10^{-1}$–10^{2} sec) bursts of cosmic γ rays monitored with spacecraft carrying special-purpose detectors. Very likely the burst sources are old ($> 10^{6}$ yr) magnetized neutron stars located fairly close to the solar system ($D \approx 10$–100 pc). A most interesting physical problem thereby awaits investigation: the nonstable behavior of ultradense matter in strong magnetic fields ($B \approx 10^{12}$–10^{13} gauss). Several nonstable processes that might generate the observed bursts are discussed.

PACS numbers: 98.70.Qy, 95.85.Qx

CONTENTS

1. INTRODUCTION

Orbiting the earth for a number of years was a family of American satellites called the Vela series. The Velas were designed chiefly to monitor any thermonuclear explosions occurring in space. In 1965 these satellites began to record transient elevations in the counting rates of their gamma-ray detectors[1]; but the cause of the phenomenon was not understood at that time. The enhanced counts, it was thought, might have resulted from hard radiation emitted by the sun during flares, from the influence of trapped radiation, or from instrumental effects.

As the seventies opened, this fairly routine activity took on a highly interesting, even intriguing cast. For it was in 1969–1970 that the Vela 5A, 6A, 6B satellites were launched, carrying improved high-resolution γ-ray detectors. Observations with the new Velas disclosed that at least some of the count enhancements being picked up by the detectors unquestionably represented peaks in the flux of γ-ray photons having energies $E_\gamma \approx 0.1$–1 MeV. The regions of the sky from which these γ rays were coming entirely ruled out solar system objects (the sun, the moon, the planets, the earth itself) from the list of candidate sources. That is how the bursts of cosmic γ rays were discovered.[2]

Even the earliest experiments recorded γ-ray bursts whose energy flux density S near the earth[2] was as high as $\approx 10^{-3}$ erg/cm^2. If the burst sources were located, say, 10 parsecs away from us, just a few times the distance of the nearest stars, then the total energy Q released in a single burst would have been fully 10^{37} erg. And this enormous energy would have been liberated mainly in the form of γ rays within a very brief interval, roughly 0.1–10 sec. In the optical range, γ-ray burst sources emit less than 10^{-2} of the energy carried by their γ rays[3]; at radio wavelengths the contribution to the total burst energy is smaller still,[4] no more than 10^{-6}. For comparison it is worth recalling that when the sun is in its quiescent state its spectrum contains hardly any γ rays; only during the most powerful flares does the solar γ-ray luminosity achieve even 10^{27} erg/sec. The bulk of the flare energy, some 10^{33} erg, is radiated instead in the optical and ultraviolet regions.

So strange were these cosmic γ-ray transients, and so fruitless was the effort to identify their sources with any astronomical objects at all observed elsewhere in the electromagnetic spectrum, that a multitude of hypotheses were put forward seeking to interpret the phenomenon.[1)] The γ-ray bursts were attributed to exceptionally powerful flares on stars,[6,7] to supernova explosions,[8] to active processes at work in the interior of neutron stars[9-11] or in their magnetospheres,[12] to impacts of comets onto neutron stars or white dwarfs,[13,14] to supermassive magnetic stars collapsing inside the nuclei of active galaxies or quasars,[15] to chuncks of antimatter colliding with normal stars,[16] and to comets made of ordinary matter striking antimatter stars.[17]

From the very start, however, preference was given to neutron stars as the burst sources. In fact, neutron stars belonging to close binary systems had already been observed to be emitting x rays at luminosities up to 10^{37}–10^{38} erg/sec. Some of those x-ray sources (Cygnus X-1, Cygnus X-3) were fairly strong γ-ray

---

1) The status of early research on γ-ray bursts was reviewed by the authors in this journal[5] in 1975.

emitters as well.[18,19] Two neutron stars, the pulsars PSR 0531 + 21 and PSR 0833 − 45, had been found to produce γ-ray photons[20] with $E_\gamma \approx 10-10^3$ MeV. The γ-ray luminosity of these pulsars, $L_\gamma \approx 10^{35}-10^{36}$ erg/sec, was roughly comparable with the luminosity to be expected for the burst sources if they were indeed galactic objects. But the nature of the γ-ray burst sources could be definitely settled only by making further observations.

As we have said, the instruments aboard the Vela satellites had not been intended for studying cosmic γ-ray bursts. They had a nonlinear time scale, poor sensitivity, and low resolution with respect to time; and they were incapable of establishing energy spectra for the bursts. If significant progress was to be made in investigating the phenomenon, special-purpose "burst" instrumentation had to be built and placed aboard spacecraft.

Now there are numerous events that can simulate γ-ray transients. Hence a cosmic burst can be considered definite only if it has been recorded by at least two vehicles well separated in space. Multiple-spacecraft observations of γ-ray bursts are also needed for fixing the direction toward the source of the γ rays. In fact, the method in current use for establishing the position of a γ-ray burst source on the celestial sphere relies on a simple relationship between the time lag Δt in the burst signals recorded by two detectors spaced a distance l apart and with the angle ϑ between the line joining the detectors and the direction toward the source: $c\Delta t = l\cos\vartheta$. By measuring Δt one can evaluate the angle ϑ and thereby describe on the celestial sphere a circle containing the burst source. If the γ-ray burst should be recorded by three detectors, then the source field will be constricted to a pair of points–the intersections of a pair of circles. The remaining ambiguity can be eliminated by employing a fourth detector mounted on a spacecraft located outside the plane that passes through the vehicles carrying the first three detectors. Since the quantities $\Delta t, l$ will not be measured to perfect accuracy, one actually will obtain a certain region, or error box, on the celestial sphere within which the burst source ought to be located (further details are given in our earlier review[5]).

The first specialized burst detector[21] began to operate in 1976 aboard the West German space probe Helios 2. This probe followed an elliptical orbit about the sun extending from the earth's orbit to that of Mercury. The second γ-ray burst experiment was the SIGNE 2M package[2)] developed jointly by Soviet and French scientists[22] and launched in 1977 on the Soviet high-apogee satellite Prognoz 6. The Helios 2 and Prognoz 6 spacecraft were separated by around 10^8 km. However, during 1977 and early 1978 only one vehicle, Helios 2, was distant from the earth; all other burst detectors were orbiting the earth. The burst source fields therefore took the form of strips crossing the sky.[23] Furthermore, the Helios 2 γ-ray detector had only a small area (21.2 cm²), so it could not record weak γ-ray bursts.

In the latter half of 1978 the situation abruptly changed, for the Soviet automated interplanetary probes Venera 11 and Venera 12 and the Prognoz 7 satellite were accompanied in space by the American Pioneer Venus Orbiter and the ISEE 3, equipped with instrumentation from the Los Alamos National Laboratory and the NASA Goddard Space Flight Center. SIGNE 2M experiments were operating on Prognoz 7 and Venera 11,12; each carried a pair of 63-cm² γ-ray detectors. In addition, six 50-cm² Cone detectors were carried by Venera 11,12. As a result the burst instruments had become over an order of magnitude more sensitive. Gamma-ray bursts were reliably recorded down to $S \approx 10^{-6}$ erg/cm², and some events were even detected in the range $S = 10^{-6}-10^{-7}$ erg/cm². By the end of 1979 more than 150 γ-ray transients had been observed; the SIGNE 2M experiment had recorded over 50, while the Cone devices had detected more than 100 bursts. These two experiments were recording γ-ray bursts at rates of about 0.1 and 0.4 event/day, on the average.

The special-purpose burst detectors have furnished a great deal of observational data, enough so that we can now say with confidence that the sources of the γ-ray bursts are relatively old neutron stars which, like the radio pulsars and such x-ray sources as Hercules X-1, have surface magnetic fields of the order of $10^{12}-10^{13}$ gauss. In this review we shall describe the outstanding properties of γ-ray bursts and then turn to the current status of the theory for this interesting astrophysical process.

2. OBSERVATIONAL DATA

a) Time structure

In duration, cosmic γ-ray bursts cover a wide range,[24-26] from 0.05 sec to ≈10² sec. The shortest burst was the one recorded on 1979 June 13 by three space probes (Venera 11,12 and PVO); it lasted 47 msec at most (Fig. 1). On a time scale with (1/512)-sec resolution the γ-ray intensity exhibits fine structure with separate microbursts of duration $t < 2$ msec. An important conclusion follows: the burst emission is being generated in a zone of size $tc \lesssim 600$ km.

Among all the γ-ray bursts recorded, the 1979 March 5 event occupies a special place. This burst differs from others in its extremely sharp (≈0.2 msec) leading front and in the high values of its energy flux density S and peak intensity.[27,28] Its most interesting feature,

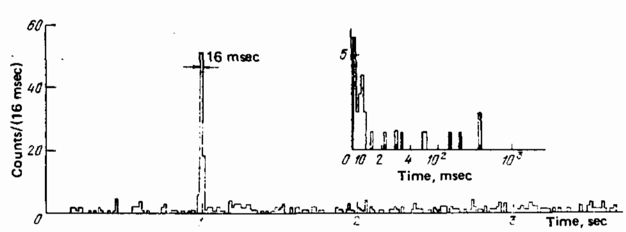

FIG. 1. Time profile of the 1979 June 13 γ-ray burst. Inset: logarithmic millisecond scale.

[2)]Solar International Gamma-ray and Neutron Experiments, modified in Russian to the acronym SNEG [snow].

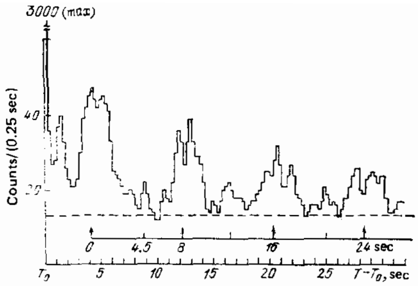

FIG. 2. Time profile of the 1979 March 5 γ-ray burst.

however, is that a short (0.25 sec) burst of γ rays is followed by a train of x-ray pulsations having a period of 8.00 ± 0.05 sec and an amplitude decaying with time (Fig. 2). A total of 22 of these x-ray pulsations were recorded during 144 sec of instrument operation.[28]

Oscillations in the burst intensity subsequent to the leading pulse were also observed in the event recorded on 1977 October 29. In this case the pulse repetition period[29] was 4.2 ± 0.2 sec.

Some of the γ-ray bursts lasting longer than 2 sec show a time profile with recurrent structural features. One example is the 1979 January 13 burst: peaks A, B, C repeat their structure with a ≈ 5.5 sec period (Fig. 3), and the duplicated features have similar energy spectra[30] (Fig. 4). The question of whether period occur in the time structure of γ-ray bursts has been examined in some detail by Pizzichini[31]; she has shown that the values of the apparent periods cluster mainly in the 2–4.5 sec range, but bursts are encountered having periods as long as 8–9 sec.

b) Energy spectrum

On the Apollo 16 mission a γ-ray burst was observed on 1972 April 27. Its energy spectrum,[32] reproduced in Fig. 5, has a typical behavior: from 2 keV to ≈ 1.5 MeV it fits the emission spectrum of optically thin plasma having $kT = 500$ keV.

Up to $E_\gamma \approx 1$ MeV the spectrum of most γ-ray bursts[25] is closely matched by the spectrum of an optically thin plasma with $kT \approx 50$–500 keV, but above ≈ 1–2 MeV some bursts differ markedly from thin plasma: their

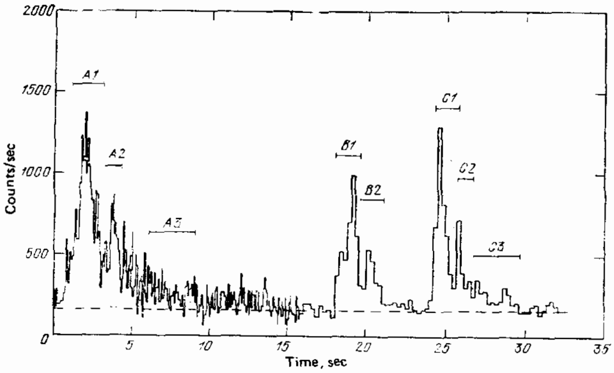

FIG. 3. Time profile of the 1979 January 13 γ-ray burst.

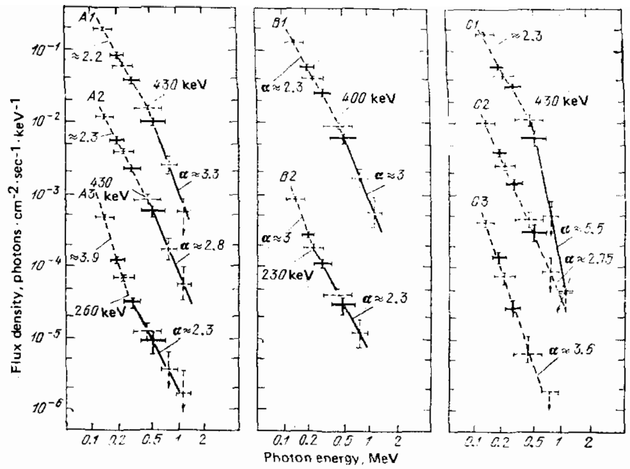

FIG. 4. Energy spectra of structural features within the peaks of the 1979 January 13 burst.

spectrum may extend to energies as high[33] as $E_\gamma \approx 9$ MeV, whereas the thermal radiation flux of plasma with $kT < 1$ MeV cuts off exponentially at high energies ($E_\gamma \gg 1$ MeV), dropping practically to zero for $E_\gamma \approx 10$ MeV.

The emission and absorption features which the Cone detectors have recorded in the energy spectra of γ-ray bursts[34] have played an important role in clarifying the nature of the burst sources (see Sec. 3b). Figure 6 illustrates the energy spectrum of the 1979 March 5 burst. Two components are present, supplemented by a well-defined, broad emission line[35] at $E_\gamma \approx 430$ keV. Similar γ-ray emission lines have been detected in the spectra of six other bursts.[34] In the 1978 November 19 burst, along with a broad 420-KeV emission line a germanium spectrometer observed a narrow line[36] at $E_\gamma = 740$ keV.

The Cone apparatus has recorded absorption lines in the 40–60 keV energy range in the spectra of about 20 γ-ray bursts.[34]

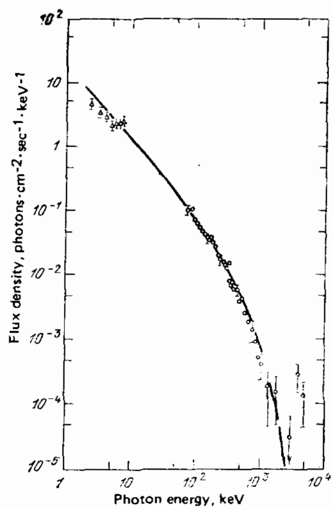

FIG. 5. Average energy spectrum of the 1972 April 27 γ-ray burst observed with the Apollo 16 spectrometer (Gilman *et al.*[32]). Solid curve: thermal bremsstrahlung spectrum of optically thin plasma with $kT = 500$ keV.

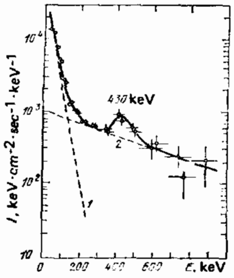

FIG. 6. Energy spectrum of the 1979 March 5 burst. There are three components: 1) hard x rays with $kT = 35 \pm 5$ keV: 2) γ rays with $kT = 520 \pm 100$ keV; 3) the γ-ray annihilation line.

c) Distribution of burst sources over the sky

Figure 7 charts the position of 63 γ-ray burst sources in galactic coordinates (longitude l^{II}, latitude b^{II}). The coordinates of about 50 of these sources have been determined from the Cone data.[37] Notice that the burst sources are distributed more or less uniformly over the celestial sphere, showing no concentration toward either the galactic center or the galactic disk.

The galactic-latitude distribution of the same[63] burst sources is indicated by the histogram of Fig. 8; if the sources were distributed uniformly over the sky, the dashed line would apply. Fully 24% of all the sources are collected in the peak at $b = -15° \pm 5°$. This peak exceeds the isotropic curve by 2.5σ. All the other departures from the isotropic distribution may be considered random. Thus at present we have no evidence that the angular distribution of γ-ray burst sources differs from isotropy, except for the modest excess count at latitudes $b \approx -15°$.

A correlation has just lately been reported[38] between the directions in which the spacecraft carrying the Cone detectors were moving and the directions toward weak γ-ray burst sources. Since the recognition of sources by Cone was sensitive to the thickness of material above the several elements of the detector, the correlation is readily understandable. The instrumental effects responsible for this correlation[38] probably have no qualitative influence on the results of the Cone experiment, so that our conclusions of Sec. 3, which rely on the Cone data, should remain valid.

Such a correlation ought to affect chiefly the angular distribution of the burst sources, producing an anisot-

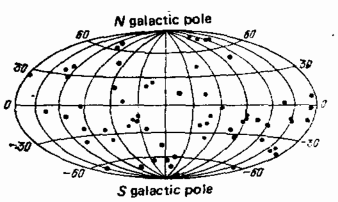

FIG. 7. Map of γ-ray burst sources in galactic coordinates.

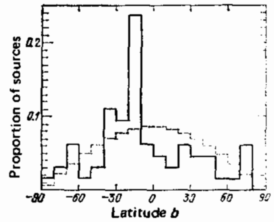

FIG. 8. Distribution of burst sources with galactic latitude b. Dashed line: an isotropic distribution.

ropy. However, the angular distributions derived from all detectors combined and from the Cone data alone are much the same.

d) Burst recurrence

Recurrent bursting was first observed for the source discovered on 1979 March 5 and designated[27] FXP (flaring x-ray pulsar) 0520 – 66. Bursts from FXP 0520 – 66 were recorded both March 5 and 6, and again on 1979 April 4 and 24. The same group reported recurrent bursts[27] from the source B1900 + 14 on 1979 March 24, 25, 27.

To interpret the peak at $b \approx -15°$ in the angular distribution of γ-ray burst sources, one of us has suggested[39] that two other recurrent sources might exist, located at $l, b = 270°, -15°$ and $32°, -15°$. The first source would have been responsible for the 1979 April 2, August 29, and September 25 bursts; the second, for the events of 1978 December 28 and 1979 February 5. Thus among the 63 burst sources whose angular coordinates are known, four would presumably be recurrent. However, the sites of the sources generally are none too accurate, so it is by no means certain that bursts are actually recurring in all these sources.

e) Integrated flux-density distribution

Since more than 150 γ-ray bursts have now been recorded (Sec. 1), the observational material is extensive enough to warrant statistical treatment. The results obtained with the IMP 7 spacecraft[40] and with the Cone and SIGNE 2M experiments on the Venera 11, 12 missions[37,39] are representative. Figure 9 indicates how the γ-ray bursts recorded by these spacecraft are distributed with respect to the energy flux density in each burst event above a common detection threshold. We see from this diagram that the number $N(>S)$ of bursts recorded annually whose integrated flux density exceeds S is practically the same for each spacecraft. In the low-S range the burst detection rate $N(>S)$ is saturated at $N \approx 200$ events/yr. The instruments aboard the spacecraft had burst recognition thresholds at levels of 10^{-6}–10^{-5} erg/cm^2, indicating that the saturation of $N(>S)$ for small S is evidently an instrumental effect.

Apart from the satellite studies of γ-ray bursts, observations have also been made by balloon (point symbols in Fig. 9). These experiments have utilized γ-ray detectors more than 1 m^2 in area, with no threshold device. Usually the balloon observations have lasted no

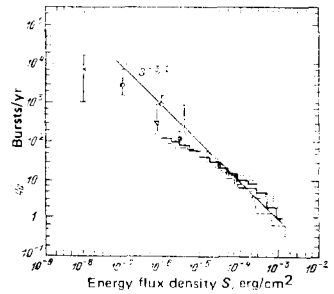

FIG. 9. Annular number $N(>S)$ of γ-ray bursts recorded with an energy flux density per burst greater than S, as a function of S. Broken lines: data from the IMP 7 spacecraft (dashed), the Cone detectors aboard Venera 11, 12 (thick solid line), the Venera 11 SIGNE 2M (thin solid line), and the Venera 12 SIGNE 2M (dotted): straight line: the $N(>S)\propto S^{-3/2}$ law: points with error bars: balloon data.

longer than 1 day. Several events have been detected in this manner[40] at a level $S\sim 10^{-8}$ erg/cm^2, although they are not confirmed by observations with other instruments. An especially interesting experiment has been performed with a pair of balloons spaced more than 1000 km apart.[41] Not a single event was observed simultaneously by both balloons. Hence it seems very likely that the "burst" events recorded in earlier balloon experiments were actually caused by charged-particle streams in space near the earth. For the time being the balloon results should therefore be regarded as merely setting upper limits on the frequency of low-intensity γ-ray bursts.

If the burst sources were distributed homogeneously and isotropically in space, and $N(>S)\propto S^{-3/2}$ law should be observed.[5] That is just what is found for strong ($S\approx 10^{-4}$–10^{-3} erg/cm^2) γ-ray bursts, but at low flux densities ($S<10^{-4}$ erg/cm^2) the $S^{-3/2}$ law is definitely violated. The observed $N(>S)$ relation may be affected by the sensitivity threshold, but in addition the burst sources may have a spread in luminosity[42] as great as a factor of $\approx 10^3$.

f) Accurate placement of burst sources and attempts at identification

In most cases the γ-ray burst sources plotted on the celestial sphere in Fig. 7 are positioned only to within a few degrees. One square degree of the sky will contain thousands of stars brighter than 21st magnitude. Thus in order to have hopes of identifying a burst source with, say, an object observed optically, an angular resolution of around 1′ or better would have to be achieved.

To date enough information has been assembled on 11 bursts recorded by Soviet and American spacecraft for their sources to be positioned in the sky to an accuracy ranging from 20 to 0.05 $(1')^2$.

The burst source fields have been inspected with optical and radio telescopes and by x-ray techniques. We summarize here the results obtained for the three γ-ray bursts whose source fields have been most fully studied.

The field containing the source of the 1979 April 6 burst is located in the high galactic latitude $b=-61°$. When the immediate region was compared against star charts, not a single object brighter than 22^m could be found. The γ-ray burst site was then photographed with the 3.6-m European Southern Observatory telescope, and three very faint ($\approx 24^m$) objects were detected. On the average a $(1')^2$ field photographed in high galactic latitudes will show two stars and four galaxies, so the number of optical objects found within the error box around the 1979 April 6 burst source was consistent with the number expected. Hence if the source is located inside our Galaxy, it should be a compact object glowing faintly in the optical range. This burst site has been examined with the HEAO B orbiting x-ray observatory; there is not evidence for any x-ray sources in the vicinity.

The source of the 1978 November 19 γ-ray burst has been positioned in the sky within an 8 $(1')^2$ error box. This object again lies in a high galactic latitude, $b=-84°$. Inside the error box HEAO B has detected a weak x-ray source, with a 0.2–3.7 keV flux density of $(1.4\pm 0.5)\cdot 10^{-13}$ erg/cm^2 at the earth. Observations with the ESO telescope has disclosed two 20^m type M stars here.[43] The region also contains two radio sources, one located at the center of the x-ray source field and the other near its edge; the radiation of the second radio sources do not coincide with the M stars. As yet there is no evidence that the x-ray source, stars, or radio sources have anything to do with the γ-ray burst source.

Perhaps the most fascinating γ-ray burst is the one observed on 1979 March 5. When its source was positioned, a surprise was in store: the first step of the process put the source within a $1'\times 1'.5$ field containing the nebula N49, the remnant of a supernova outburst that occurred some 10^4 yr ago in the Large Magellanic Cloud. Further constriction of the γ-ray burst site to a $5''\times 30''$ box placed the source in the northern part of that nebula. If the burst source is indeed located inside N49, its distance would be 55 kpc, and the energy released as γ radiation during the flare responsible for the March 5 burst would have amounted to $\sim 10^{44}$ erg. The HEAO B satellite had observed N49 prior to the March 5 event and two weeks afterward; to a level of 0.8% there were no fluctuations in the x-ray emission of N49, so that no sign was observed of any consequences of the γ-ray burst which might have supported the idea that the burst source is associated with the nebula.

3. THEORETICAL INTERPRETATION OF BURST DATA

Once the γ-ray bursters had been discovered, theory had to fact the following questions: where are the burst sources located, what class of astronomical objects do they represent, and what mechanism is generating the burst of γ rays? Let us take each of these questions in turn.

a) Distance

From the fact that the γ-ray burst sources are distributed isotropically over the sky, we may infer that they either lie nearby, at distances less than the thickness of the galactic disk (within a few hundred parsecs of us), or far off in extragalactic space (more than 10 megaparsecs away). That the γ-ray burst might possibly be of extragalactic origin is suggested by the matching positions of the powerful 1979 March 5 burst source and the nebula N49 which has resulted from a supernova outburst in one of the closest galaxies, the Large Magellanic Cloud; but so far that is the only argument for the hypothesis that the burst sources are extragalactic.

Such a hypothesis would, on the contrary, pose not a few serious difficulties. In particular, if the flare responsible for the March 5 burst did occur in the LMC, the peak luminosity of the source would have reached 10^{44} erg/sec. From the observed rise time of the pulse *it would appear that the γ-ray emission zone measures* less than 10^9 cm across. In a powerful hard–x-ray and γ-ray source as compact as this, the photon density would be so high that, in seeking to escape from the source, γ-ray photons of energy $E_\gamma \gtrsim mc^2$ would be absorbed, forming electron–positron pairs.[15,44-46]

If the source is radiating isotropically, a photon of energy $E_\gamma \gtrsim mc^2$ will encounter an optical depth[46] of roughly

$$\tau = \frac{\sigma_0 mc^2 F(mc^2)\, D^2}{lc}, \qquad (1)$$

where σ_0 is the Thomson cross section, $F(E_\gamma)$ represents the observed differential emission spectrum of the burst at energy E_γ, D is the distance of the source, l is the diameter of the emission zone, and m is the mass of an electron. Applying Eq. (1), we see that if the March 5 burst originated in the LMC, the optical depth for $E_\gamma \gtrsim mc^2$ photons would greatly exceed unit ($\tau \gtrsim 10^5$), so we ought not have observed such photons. But the burst emission spectrum did extend up to 2.5-MeV energy, if not beyond, indicating that the source should have been optically thin to these energetic photons ($\tau < 1$).

It follows that if the March 5 burst source was an isotropic emitter,[46] its distance $D < 200$ pc. As will be shown in Sec. 3b, all the observational evidence, taken together, points to the conclusion that the sources of the γ-ray bursts are neutron stars. In that event the size of the emission region[47] would be $l \lesssim 10^6$–10^7 cm. With $\tau < 1$, Eq. (1) would then set an even sharper limit on the distance of the March 5 burst source[46]: $D < 5$–20 pc.

In the bursts of some sources, γ-ray photons as energetic as 9 MeV have been recorded (Sec. 2b). On analyzing the x- and γ-ray spectra of these bursts one finds no evidence for a cutoff at the high-frequency end. Hence the sources evidently are optically thin ($\tau < 1$) for $E_\gamma > mc^2$ and are located within a few dozen parsecs of us.

One arrives at equally small distance estimates by recognizing that a good fit to the spectra of many γ-ray bursts is given by the bremsstrahlung spectrum of optically thin plasma[25] at temperature $kT \approx 50$–500 keV. The bremsstrahlung mechanism will produce a luminosity

$$\Phi_{ff} = 2\cdot 10^{-27} T^{1/2} n_e^2 \text{ erg/sec} \qquad (2)$$

per unit volume, where T is the electron temperature in in kelvins and n_e denotes the number of electrons in 1 cm^3. For bursts recorded with an energy flux density I at the earth, the luminosity is

$$\Phi_{ff} = \frac{4\pi D^2 I}{V}; \qquad (3)$$

here V is the volume of the emission region.

To illustrate, let us take the 1972 April 27 burst recorded[32] on Apollo 16. This γ-ray burst peaked sharply (rise time $t \approx 110$ msec); the emission spectrum averaged over the total burst duration (≈ 15 sec), corresponded to $kT \approx 500$ keV, with a high-energy exponential cutoff. *The measured width of the leading front sets a* limit on the diameter of the γ-ray emission zone: $l \lesssim ct \approx 10^9$ cm. Since the source has a small optical depth ($n_e \sigma_0 l \lesssim 1$), its electron density is limited to $n_e < 10^{15}$ cm^{-3}. With these constraints as well as Eqs. (2), (3) and the measured flux density $I \approx 2.5\cdot 10^{-5}$ $erg\cdot cm^{-2}\cdot sec^{-1}$ we may conclude[32] that the April 27 burst source was no more than 50 pc away.

Estimates similar to those just given suggest that the γ-ray bursts which have been observed are coming from sources typically at distances of 10–100 pc.

b) Nature of sources

The upper bound $l \lesssim 10^8$–10^9 cm which the burst flux variability placed on the size of the emission zone implied in itself that the burst sources were compact astrophysical objects. But this fact was not definitely proved until quite recently, when the sources began to be accurately positioned on the celestial sphere. The error boxes around the sources of several bursts (Sec. 2f) have been found to contain only a few exceedingly faint optical objects, not distinctive in any way and presumably having no connection with the bursts observed. Upper limits sets on the luminosity of the γ-ray burst sources in their quiet state indicate that the objects in question are either white dwarfs or neutron stars.

The following observational data are decisive for choosing between these alternatives:

a. Emission lines at $E_\gamma \approx 0.4$ and 0.7 MeV occur in some burst spectra,[34-36] as well as absorption lines at x-ray energies $E_x \approx 40$–60 keV.

b. Flux variations with a cycle of several seconds are encountered in some γ-ray bursts.[28-31]

A natural explanation of all these facts is afforded only by the model wherein the γ-ray burst source is a spinning neutron star with a surface magnetic field strength $B \approx 10^{12}$–10^{13} gauss. The 0.4- and 0.7-MeV emission lines would then be identifiable with redshifted γ-ray lines emitted at 0.511 and 0.847 MeV, respectively.[34-36] The first of these would result from two-photon $e^{\pm}$ annihilation, while the second would be emitted by excited iron nuclei, which should be abundant in the outer layers of neutron stars. That the observed γ-ray lines are redshifted by $\approx 20\%$ can be readily attributed to the gravitational shift which the photons will suffer as they escape from the neutron star's intense gravitational field. The absorption features in the burst x-ray spectrum would presumably arise[34] when radiation is absorbed near the cyclotron frequency $\omega_B = eB/mc \approx 10^{19}[B/(10^{12}\text{ gauss})]\text{ sec}^{-1}$ in the 10^{12}–10^{13} gauss magnetic field. And the periodic fluctuations in the burst intensity can be ascribed in a natural way, just as with radio pulsars and x-ray binary systems like Her X-1, to the spin of a neutron star radiating anisotropically. The rotation periods of the neutron stars responsible for the γ-ray bursts are relatively long, about 4–8 sec, indicating that these stars are older than the radio pulsars. On the average, the neutron-star sources of the γ-ray bursts are a good deal more than 10^6 yr old.

c) Properties of burst generation zone

Near the surface of a neutron star the emission of the gas will be controlled mainly by the temperature, the particle density, and the magnetic field strength. The temperature of the gas in a γ-ray burst source is $kT \approx 50$–500 keV (Sec. 3a). To estimate the range of admissible values for the paricle density in the source, let us first evaluate the maximum density $n_{\max}$. We shall suppose for this purpose that no energy is pumped into the particles during a flare event. Then the total number of particles in the source will be

$$N = \frac{Q}{(3/2)\,kT} \approx 10^{44}\left(\frac{Q}{10^{37}\text{ erg}}\right)\left(\frac{T}{10^9\text{ K}}\right)^{-1}, \qquad (4)$$

where Q denotes the total energy released in the flare. The source will have a volume

$$V = 4\pi R^2 \alpha l \approx 10^{19}\left(\frac{\alpha l}{10^6\text{ cm}}\right)\text{cm}^3; \qquad (5)$$

here $R \approx 10^6$ cm is the radius of the neutron star, and α is the fraction of its surface occupied by the burst source. Equations (4),(5) now give

$$n_{\max} = \frac{N}{V} \approx 10^{25}\left(\frac{Q}{10^{37}\text{ erg}}\right)\left(\frac{T}{10^9\text{ K}}\right)^{-1}\left(\frac{\alpha l}{10^6\text{cm}}\right)^{-1}\text{cm-3}. \qquad (6)$$

The principal mechanisms for generating emission in the hot plasma at the surface of a magnetized neutron star are bremsstrahlung and cyclotron radiation, as well as $e^{\pm}$ annihilation. To estimate the minimum possible particle density $n_{\min}$ in the source we have to decide which of these mechanisms will be most efficient.

Bremsstrahlung, cyclotron radiation, and annihilation radiation will serve to cool the plasma on time scales[48]

$$t_{\text{ff}} \approx 4.4\cdot 10^{-11} Z^{-2}\left(\frac{n}{10^{26}\text{ cm}^{-3}}\right)^{-1}\left(\frac{T}{10^9\text{ K}}\right)^{1/2}\text{ sec},$$

$$t_{\text{cy}} \approx 3.9\cdot 10^{-16}\left(\frac{B}{10^{12}\text{ Гsec}}\right)^{-2}\text{ sec},$$

$$t_{\text{gauss}} \approx 1.3\cdot 10^{-12}\left(\frac{n}{10^{26}\text{ cm}^{-3}}\right)^{-1}\text{ sec},$$

respectively, where Z is the atomic number of the nuclei in the radiating plasma. If $n < n_{\max}$, $T \approx 10^9$–10^{10} °K, and $B \approx 10^{12}$–10^{13} gauss we will have $t_{\text{ff}}, t_{\text{an}} \gg t_{\text{cy}}$. Hence the plasma will be cooled most effectively by cyclotron radiation.

The minimum particle density in the source will now be given by the condition that

$$V\Phi_{\text{cy}} t = Q; \qquad (7)$$

here t is the duration of the flare process, and

$$\Phi_{\text{cy}} = n\sigma_0 c\,\frac{B^2}{2\pi}\,\frac{kT}{mc^2} \approx 5\cdot 10^{34}\left(\frac{n}{10^{26}\text{ cm}^{-3}}\right)\left(\frac{B}{10^{12}\text{ gauss}}\right)^2\left(\frac{T}{10^9\text{ K}}\right)\text{erg}\cdot\text{cm}^{-3}\cdot\text{sec}^{-1} \qquad (8)$$

represents the volume emissivity of the gas due to the cyclotron mechanism. Substituting the expressions (5), (8) into Eq. (7), we arrive at a minimum particle density

$$n_{\min} \approx 10^9\left(\frac{Q}{10^{37}\text{ erg}}\right)\left(\frac{B}{10^{12}\text{ gauss}}\right)^{-2}\left(\frac{T}{10^9\text{ K}}\right)^{-1}\left(\frac{t}{1\text{ sec}^{-1}}\right)^{-1}\left(\frac{\alpha l}{10^6\text{ cm}}\right)^{-1}\text{cm}^{-3}. \qquad (9)$$

We easily see that if $n = n_{\max}$ the source will be optically thick ($n_{\max}\sigma_0 l \gg 1$). If instead $n = n_{\min}$, the gas will have a small optical depth ($n_{\min}\sigma_0 l \ll 1$), and energy would have to be injected into the radiating particles during the flare.

d) Nature of flare process

Little study has been given thus far to the character of the flares which generate the observed bursts of hard radiation. The reason is that flares on magnetoactive neutron stars will be triggered by nonstable processes taking place under extreme physical conditions that differ fundamentally from conditions which can be simulated in the laboratory. First let us consider what energy sources are available on neutron stars that would be powerful enough to produce the γ-ray bursts.

Neutron stars are responsible for two classes of well-studied astronomical objects (Sec. 3b): radio pulsars and x-ray sources in close binary systems. In pulsars the radiation is supported by the kinetic energy of the spinning neutron star. In x-ray binaries, however, the energy source is the gravitational energy liberated as the neutron star accretes gas flowing out of the companion normal star. The neutron stars responsible for γ-ray bursts might, in principle, have an energy source of the same kind. In fact, for a typical burst source spinning at an angular velocity $\Omega \approx 1\text{ sec}^{-1}$, with the neutron star having a moment of inertia $I \approx 10^{44}$–$10^{45}\text{ g}\cdot\text{cm}^2$, the rotational kinetic energy is $I\Omega^2/2 \approx 10^{44}$–$10^{45}$ erg, far above the energy output $Q \approx 10^{37}$–10^{38} erg of γ-ray burst sources.

If the accreting neutron-star model is to account for the bursts, the accreting gas flow should have a mass $\Delta M \approx Q/0.1c^2 \approx 10^{17}$–$10^{18}$ g. That is comparable with the mass of the comets observed in our solar system. In principle, then, the γ-ray bursts might result from comets impacting neutron stars.[13,14] But this model is open to a serious objection: in order to understand why bursts can recur at intervals of a few months or even days, comets would have to be concentrated many orders of magnitude more thickly around the neutron stars than around the sun.

As material is accreted onto the neutron-star surface, light elements may accumulate and, if their density is high enough, synthesize to produce a thermonuclear explosion.[49]

Neutron stars are currently believed to have a solid crust,[50] and if they are massive enough their core may be solid as well.[51] As a neutron star gradually spins down, its flattening will diminish, causing elastic shear stresses to build up in its crust and core. These stresses could be associated with an energy[11] as great as $\approx 10^{47}-10^{48}$ erg. The solid material in the stressed regions could develop cracks from time to time, releasing some of the energy associated with the elastic shear forces. Working on this hypothesis, one would seek to extrapolate basic concepts and laws to the domain of matter in an extreme state, allowing a fundamental parameter of any solid body, its density ρ, to grow by many orders of magnitude (remember that in the core of of a neutron star $\rho \approx 10^{15}$ g/cm^3). Whether such an extrapolation is warranted remains an open question.

One other possible energy source in a neutron star has been suggested.[9,52] Free neutrons and nuclei over-enriched in neutrons might form a nonequilibrium layer which could persist[52] at densities ranging from 10^{10} to 10^{12} g/cm^3. The total energy in this nonequilibrium layer might reach $\approx 10^{48}$ erg. As the neutron-enriched material migrates into lower-density regions, say through cracks in the core or crust of the neutron star, a nuclear explosion would occur. This conjecture ties the nature of the γ-ray bursts into a very acute problem facing nuclear physics: the existence of superheavy nuclei. According to the model that Bisnovatyĭ-Kogan *et al.* propose,[9,52] the nonequilibrium layer would contain nuclei of atomic weight $A \gtrsim 300$. On being ejected from the neutron-star surface these nuclei would disintegrate, making a significant contribution to the chemical composition of the matter in the universe. The process ought to create double magic-number and therefore presumably stable $_{114}A^{298}$ nuclei. However, esperimental searches for superheavy nuclei such as these indicate[53] that they are less than 10^{-7} as abundant as uranium nuclei. Herein lies a real difficulty with the model.

To summarize, neutron stars have available the following energy sources which, in principle, might sustain the energy requirements of the γ-ray bursts:

1. The spin of the neutron star.

2. Accretion of matter onto the neutron star.

3. Thermonuclear explosions of surface material enriched in light elements.

4. Elastic shear stresses in the solid crust and core.

5. Nuclear explosions in a nonequilibrium layer abundant in free neutrons and neutron-enriched heavy nuclei.

In order for any model source to account for the observed properties of γ-ray bursts, an energy $Q \approx 10^{38}$ erg would have to be released in an interval $t \lesssim 0.1-10$ sec. Let us estimate the rate at which the rotational energy of the neutron star would be transformed into observable radiation.

From pulsar theory we know that the most effective mechanism for transforming the kinetic energy of a spinning neutron star into radio emission is braking by the star's magnetic field. The rate of energy output by this process cannot much exceed the power

$$L_{\rm md} \simeq \frac{B_s^2 R^6 \Omega^4}{c^3} \approx 10^{28} \left(\frac{B}{10^{12}\ \text{gauss}}\right)^2 \left(\frac{\Omega}{1\ \text{sec}^{-1}}\right)^4 \text{erg/sec} \qquad (10)$$

of the magnetic-dipole losses; here B_s is the magnetic field strength on the neutron-star surface.

In the case of the neutron stars responsible for the γ-ray bursts, $B_s \approx 10^{12}-10^{13}$ gauss and $\Omega \approx 1$ sec^{-1}, so $L_{\rm md}$ would be inadequate to furnish the luminosity $L \approx 10^{38}-10^{39}$ erg/sec generated during flare events. Thus while the kinetic energy of the spinning neutron star would be large enough to produce the total energy released in a flare, it evidently cannot be converted rapidly into radiation.

For all the other processes listed above, the requisite burst energy could indeed be liberated on the surface or in the interior of a neutron star in a very short time, of order $R/c \approx 10^{-4}$ sec. If that happens, then, whatever the energy source may be, a powerful shock wave will develop, and much of its energy will be thermalized in the surface layers of the neutron star. As a result the star will acquire a hot spot. Let us consider, then, the radiation of a hot, optically thick spot on the surface of a neutron star. For the time being we shall neglect effects associated with the presence of a magnetic field in the source.

A star in hydrostatic equilibrium should have a surface temperature below the Eddington value[51]

$$T_E \approx 2 \cdot 10^7 \mu^{1/4} \left(\frac{M}{M_\odot}\right)^{1/4} \left(\frac{R}{10^6\ \text{cm}}\right)^{-1/2} {}^\circ\text{K}, \qquad (11)$$

such that the force exerted on the gas and tending to eject it from the stellar surface is balanced by the force of gravity (here μ is the mean molecular weight of the gas particles; M is the mass of the star).

In the region where the burst emission is generated, the gas will typically have a temperature $T \approx 2 \cdot 10^9$ °K. Then the ratio of the radiation-pressure and gravitational forces will be of order $(T/T_E)^4 \sim 10^8$. Gravity will therefore be incapable of inhibiting the outflow of matter from the hot spot onto the neutron-star surface. This outflow will cause the bulk of the energy released in the spot to be converted into kinetic energy of the outgoing plasma. The hot spot will thereby emit γ rays on a time scale $\Delta t \approx 10^{-12}$ sec. The total amount of energy liberated in the γ-ray region of the spectrum,[51]

$$Q \approx 10^{33} \left(\frac{R}{10^6\ \text{cm}}\right)^2 \left(\frac{T}{10^9\ \text{K}}\right)^4 \text{erg}, \qquad (12)$$

will be comparatively modest, not enough to supply the energy requirements of the bursts.

Now let the neutron star have a magnetic field B satisfying the condition

$$nkT + \frac{1}{3}\sigma T^4 < \frac{B^2}{8\pi} \qquad (13)$$

(σ is the Stefan–Boltzmann constant). The field will restrain the plasma from flowing out of the star, and as a result most of the thermal energy of the gas will be radiated in the x- and γ-ray regions. For particle densities $n \leq n_{max}$ and temperatures $T \approx 10^9$–10^{10} °K, the ratio of the gas pressure nkT to the radiation pressure $\sigma T^4/3$ will be much smaller than unity. Hence the criterion (13) may be rewritten as

$$kT \leqslant 170 \sqrt{\frac{B}{10^{12}\,\text{gauss}}}\ \text{keV}. \tag{14}$$

The inequality (14) implies that in magnetic fields $B \approx 10^{12}$–10^{13} gauss the upper bound on the temperature of the hot spot on the neutron-star surface will be comparable with the observed burst radiation temperatures.

In addition to a hot spot developing, a disturbance might occur in the neutron-star magnetosphere, causing particles to be acclerated to relativistic energies.[11,12] Particles of this kind are presumably responsible for generating the nonthermal γ rays observed in bursts at photon energies $E_\gamma \gtrsim 1$ MeV. As yet, however, the processes involved have not been much explored.

4. SUMMARY AND OUTLOOK

Cosmic γ-ray bursts were discovered about a decade ago with equipment designed for entirely different purposes. In 1977–1978 spacecraft came into operation carrying first-generation instruments specially built for monitoring γ-ray bursts. The main outcome of the research so far is that today we can be confident that the burst sources are neutron stars located some 10–100 parsecs away from the solar system.

Just why is it that *old* neutron stars are displaying so much activity? What we know about stellar evolution points to an opposite tendency: neutron stars should become less active as they age. This inconsistency may come about because we are recording γ-ray bursts generated nearby ($D \approx 10$–100 pc), whereas young pulsars tend to be roughly 1000 pc away, and we cannot yet detect their bursts. It will therefore be an urgent task to improve the sensitivity of γ-ray burst detectors by at least two orders of magnitude. Moreover, by conducting such observations over long enough periods, say a year, we may be able to discern a concentration of burst sources toward the galactic plane, and thereby confirm once and for all that they do belong to our Galaxy.

Farther off is the most interesting prospect of measuring the angular coordinates of burst sources to high precision (≈1″). Then by applying the standard astronomical technique of determining the heliocentric parallax we will be able to establish the distance of the closest ($D \lesssim 10$ pc) sources and thus take a major step forward in clarifying the nature of the cosmic γ-ray bursts.

[1] R. W. Klebesadel, in: Proc. Conf. Transient Cosmic Gamma- and X-Ray sources (Sept. 1973), Los Alamos Rep. 5505-C (1974), p. 1.

[2] R. W. Klebesadel, I. B. Strong, and R. A. Olson, Astrophys. J. 182, L85 (1973).

[3] J. E. Grindlay, E. L. Wright, and R. E. McCrosky, Astrophys. J. 192, L113 (1974).

[4] V. S. Troitskiĭ, L. N. Bondar', and A. M. Starodubtsev, Usp. Fiz. Nauk **113**, 719 (1974) [Sov. Phys. Usp. **17**, 607 (1975)].

[5] O. F. Prilutskiĭ, I. L. Rozental', and V. V. Usov, Usp. Fiz. Nauk **116**, 517 (1975) [Sov. Phys. Usp. **18**, 548 (1976)].

[6] F. W. Stecker and K. J. Frost, Natura Phys. Sci. **245**, 70 (1973).

[7] K. Brecker and P. Morrison, Astrophys. J. **187**, L97 (1974).

[8] S. A. Colgate, Astrophys. J. **187**, 333 (1974).

[9] G. S. Bisnovatyĭ-Kogan, V. S. Imshennik, D. K. Nadëzhin, and V. M. Chechëtkin, Astrophys. Space Sci. **35**, 3 [**35**, 23] (1975).

[10] Yu. M. Bruk, Astrofizika **11**, 97 (1975) [Astrophysics **11**, 62 (1976)].

[11] A. I. Tsygan, Astron. Astrophys. **44**, 21 (1975).

[12] F. Pacini and M. Ruderman, Nature **251**, 399 (1974).

[13] M. Harwit and E. E. Salpeter, Astrophys. J. **186**, L37 (1973).

[14] I. S. Shklovskiĭ, Astron. Zh. **51**, 655 (1974) [Sov. Astron. **18**, 390 (1974)].

[15] O. F. Prilutskiĭ and V. V. Usov, Astrophys. Space Sci. **34**, 387 [**34**, 395] (1975).

[16] S. Sofia and H. M. Van Horn, Astrophys. J. **194**, 593 (1974).

[17] P. I. Fomin, Izv. Krym. Astrofiz. Obs. **54**, 340 (1976).

[18] R. E. Baker, R. R. Lovett, K. J. Orford, and D. Ramsden, Natura Phys. Sci. **245**, 18 (1973).

[19] B. M. Vladimirskiĭ, A. A. Stepanyan, and V. P. Fomin, Astron. Zh. **50**, 449 (1973) [Sov. Astron. **17**, 289 (1973)].

[20] G. G. Lichti, R. Buccheri, P. Caraveo, *et al.*, in: Non-Solar Gamma Rays (COSPAR sympos., Bangalore, May 1979), ed. R. Cowsik and R. D. Wills (Adv. Space Explor. **7**), Pergamon (1980), p. 49.

[21] T. L. Cline, U. D. Desai, G. Pizzichini, *et al.*, Astrophys. J. **229**, L47 (1979).

[22] M. Neil, K. Hurley, G. Vedrenne, I. V. Éstulin, and A. S. Melioranskiĭ, Astrophys. Space Sci. **42**, 99 (1976).

[23] I. V. Éstulin, T. L. Cline, G. Vedrenne, A. V. Kuznetsov, G. A. Mersov, M. Niel, B. L. Novak, and K. Hurley, Pis'ma Astron. Zh. **5**, 585 (1979) [Sov. Astron. Lett. **5**, 313 (1980)].

[24] E. P. Mazets and S. V. Golenetskiĭ, Sov. Sci. Rev. E: Astrophys. Space Phys. Rev. **1**, 205 (1981).

[25] E. P. Mazets, S. V. Golenetskiĭ, V. N. Il'inskiĭ, *et al.*, "Catalog of cosmic γ-ray bursts from the Cone experiment data," Preprint Fiz.-Tekh. Inst. Ioffe Akad. Nauk SSSR Nos. 618, 637, 662 (1979–80); Astrophys. Space Sci. **80**, 3-143 (1981).

[26] V. M. Zenchenko, A. V. Kuznetsov, G. A. Mersov, I. V. Estulin, G. Vedrenne, M. Niel, and K. Hurley, Pis'ma Astron. Zh. **6**, 208 (1980) [Sov. Astron. Lett. **6**, 114 (1980)].

[27] S. V. Golenetskiĭ, E. P. Mazets, V. N. Il'inskiĭ, and Yu. A. Gur'yan, Pis'ma Astron. Zh. **5**, 636, 641 (1979) [Sov. Astron. Lett. **5**, 340, 343 (1980)].

[28] T. L. Cline, U. D. Desai, G. Pizzichini, *et al.*, Astrophys. J. **237**, L1 (1980).

[29] K. S. Wood, E. T. Byram, T. A. Chubb, H. Friedman, J. F. Meekins, G. H. Share, and D. J. Yentis, Astrophys. J. **247**, 632 (1981).

[30] C. Barat, G. Chambon, K. Hurley, M. Niel, G. Vedrenne, I. V. Estulin, A. V. Kuznetsov, and V. M. Zenchenko, Report to 23rd COSPAR meeting, Budapest (June 1980); Astrophys. Space Sci. **75**, 83 (1981).

[31] G. Pizzichini, Astrophys. Space Sci. **75**, 205 (1981).

[32] D. Gilman, A. E. Metzger, R. H. Parker, L. G. Evans, and J. I. Trombka, Astrophys. J. **236**, 951 (1980).

[33] G. H. Share, J. D. Kurfess, S. Dee, *et al.*, in: Gamma-Ray Transients and Related Astrophysical Phenomena (La Jolla, Aug. 1981), Am. Inst. Phys. Conf. Proc. No. 77, 45 (1982).

[34] E. P. Mazets, S. V. Golenetskiĭ, R. L. Aptekar', Yu. A. Gur'yan, and V. N. Il'inskiĭ, Pis'ma Astron. Zh. **6**, 706 (1980) [Sov. Astron. Lett. **6**, 372 (1981)].

[35] E. P. Mazets, S. V. Golenetskiĭ, Yu. A. Gur'yan, and V. N.

Il'inskiĭ, Preprint Fiz.-Tekh. Inst. Ioffe Akad. Nauk SSSR No. 738 (1981).
[36]B. J. Teegarden and T. L. Cline, Astrophys. J. **236**, L67 (1980).
[37]E. P. Mazets, S. V. Golenetskiĭ, R. L. Aptekar', Yu. A. Gur'yan, and V. N. Il'inskiĭ, Pis'ma Astron. Zh. 6, 609 (1980) [Sov. Astron. Lett. **6**, 318 (1981)].
[38]J. G. Laros, W. D. Evans, E. E. Fenimore, and R. W. Klebesadel, Los Alamos Natl. Lab. Rep. LA-UR-82-936 (1982); Bull. Am. Astron. Soc. **14**, 619 (1982).
[39]I. V. Éstulin, Kosm. Issl. **20** (1982) [Cosmic Res. **20** (1983)].
[40]T. L. Cline, U. D. Desai, W. K. H. Schmidt, and B. J. Teegarden, Nature **266**, 694 (1977).
[41]K. Beurle, A. Bewick, J. S. Mills, and J. J. Quenby, Astrophys. Space Sci. **77**, 201 (1981).
[42]V. M. Zenchenko, A. V. Kuznetsov, I. V. Éstulin, G. Vedrenne, M. Niel, and K. Hurley, Kosm. Issl. **17**, 820 (1979) [Cosmic Res. **17** (1980)].
[43]G. Pizzichini, J. Danziger, P. Grosbøl, *et al.*, in: X-Ray Astronomy (15th ESLAB sympos., Amsterdam, June 1981), Space Sci. Rev. **30**, 467 (1981).
[44]G. Cavallo and M. J. Rees, Mon. Not. R. Astron. Soc. **183**, 359 (1978).
[45]W. K. H. Schmidt, Nature **271**, 525 (1978).
[46]F. A. Agaronyan and L. M. Ozernoĭ, Astron. Tsirk. No. 1072, 1 (1979).
[47]S. L. Shapiro and E. E. Salpeter, Astrophys. J. **198**, 671 (1975).
[48]D. Q. Lamb, op. cit.,[33] p. 249.
[49]H. M. Van Horn and C. J. Hansen, Astrophys. J. **191**, 479 (1974).
[50]V. L. Ginzburg, Usp. Fiz. Nauk **103**, 393 (1971) [Sov. Phys. Usp. **14**, 83 (1971)].
[51]D. Pines, J. Shaham, and M. Ruderman, Nature Phys. Sci. **237**, 83 (1972).
[52]G. S. Bisnovatyĭ-Kogan and V. M. Chechëtkin, Usp. Fiz. Nauk **127**, 263 (1979) [Sov. Phys. Usp. **22**, 89 (1980)].
[53]G. N. Flerov and V. N. Kuznetsov, Khimiya i Zhizn' (1981), No. 8, 30.

Translated by R. B. Rodman